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Stress and strain gradient in the deformed metallic surface

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Surface deformation introduces gradient structure

A gradient structure produced by surface plastic deformation with characteristics:

- Limited extension of the deformed surface layer to a depth of several mms to ~ 1 mm;
- Structural scale from nanometers to tens of micrometers increasing with increasing distance from the surface;
- Increasing strength with increasing structural fineness.

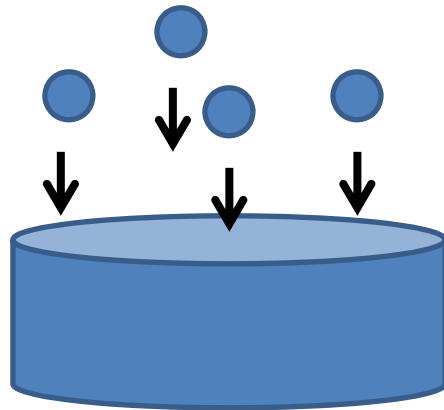
Other factors: residual stresses, chemical effects, surface morphology and roughness.

How to evaluate the stress and strain from the surface deformation microstructure ?

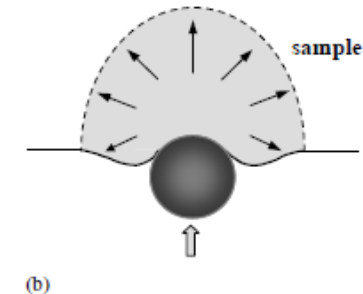
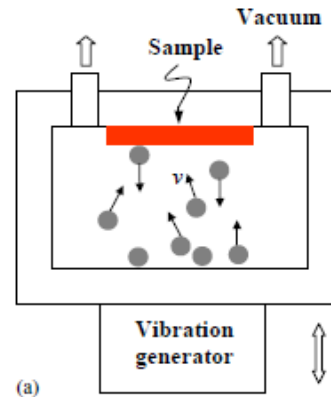
Gradient nanostructures - processing

- Shot peening;
- Surface mechanical attrition (SMAT);
- Deep rolling;
- Surface mechanical grinding (SMGT);
- Friction and sliding;
- Wear.

Shot-peening

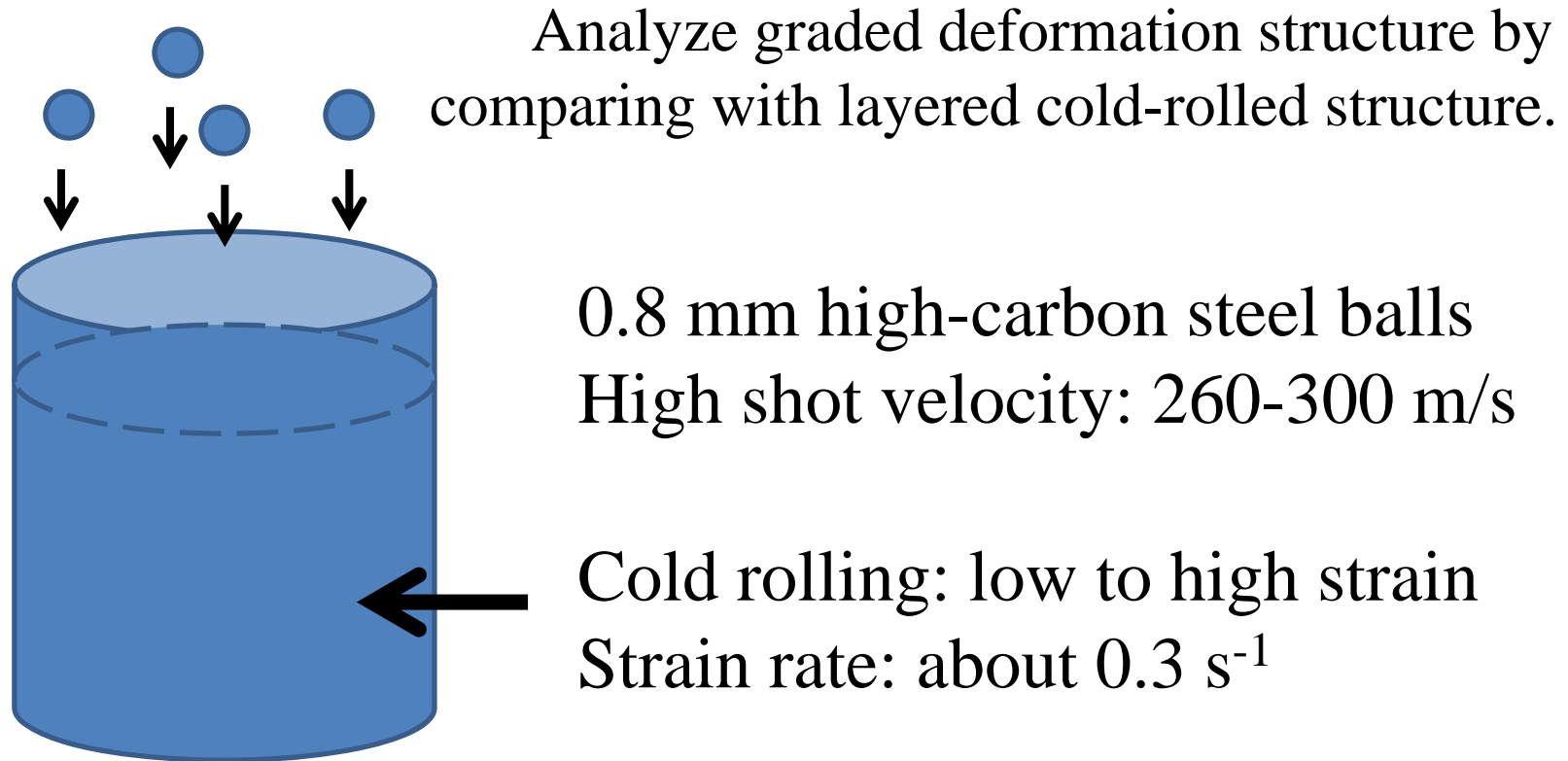


SMAT (surface mechanical attrition treatment)



	Shot-peening	SMAT
Shot size	0.05 ~ 1 mm	1 ~ 10 mm
Shot velocity	~ 100 m/s	1 ~20 m/s
Shot direction	Single direction ($\sim 90^\circ$)	Multi-direction (vibration frequency: 20 ~ 50 HZ)
Temperature increase	50-100 °C	50-100 °C
Thickness of graded nanostructures	~ 100 μm – 1 mm	~ 40 μm – 1 mm

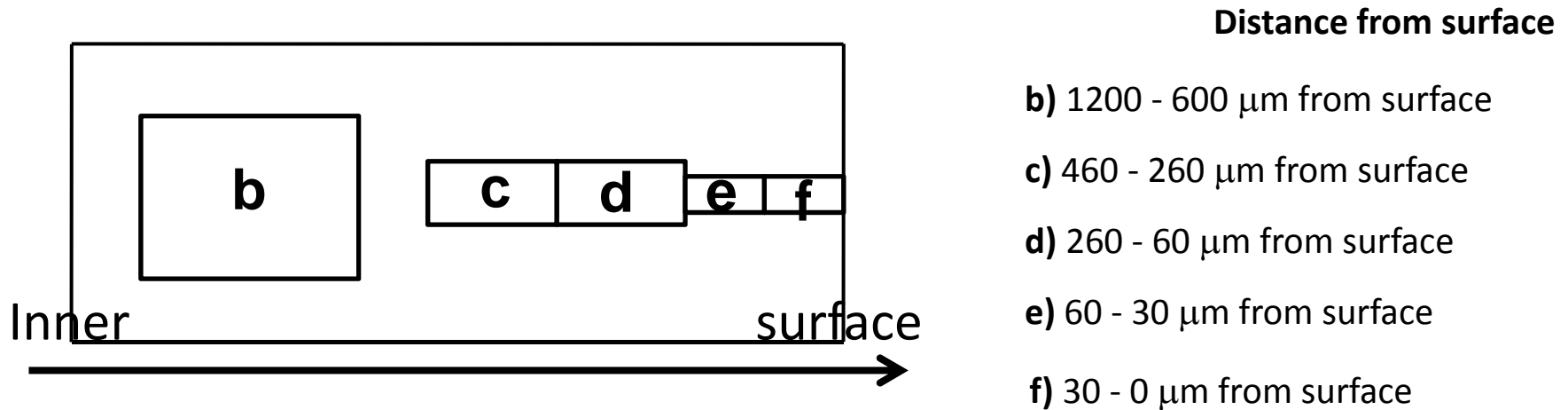
Shot Peening (1)



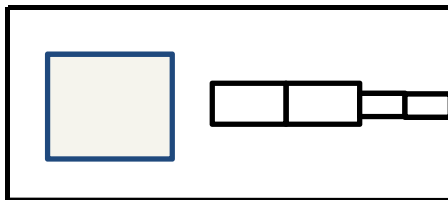
Material

Pure industrial iron: Fe-0.004C-0.44Al-0.017Ni-0.13Mn-0.0066P

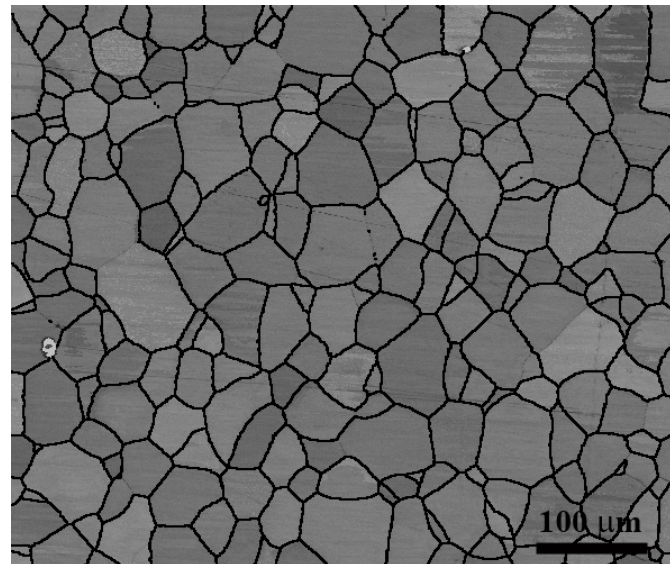
Shot-peening (2)



b: 1200 - 600 μm from surface



Inner

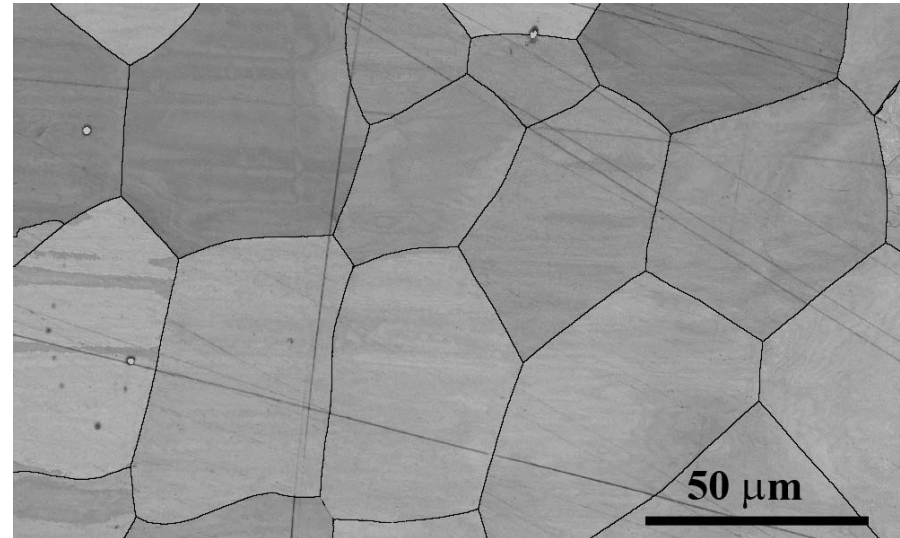
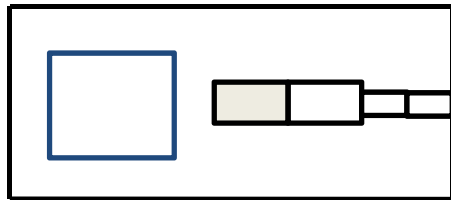


surface

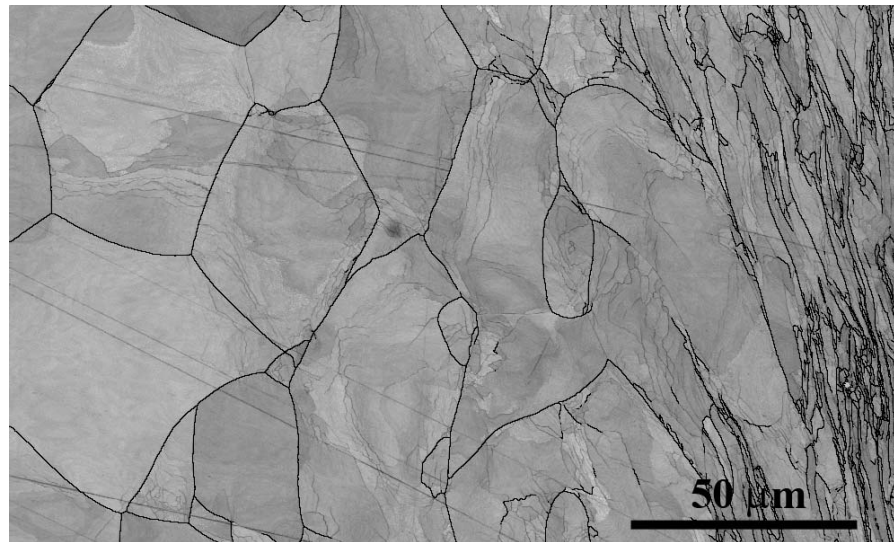
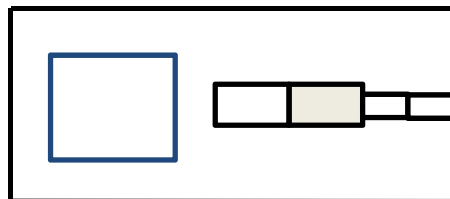
Black line: high angle boundary (Misorientation angle $> 15^\circ$)

Shot-peening (3)

c: 460 - 260 μm from surface



d: 260 - 60 μm from surface



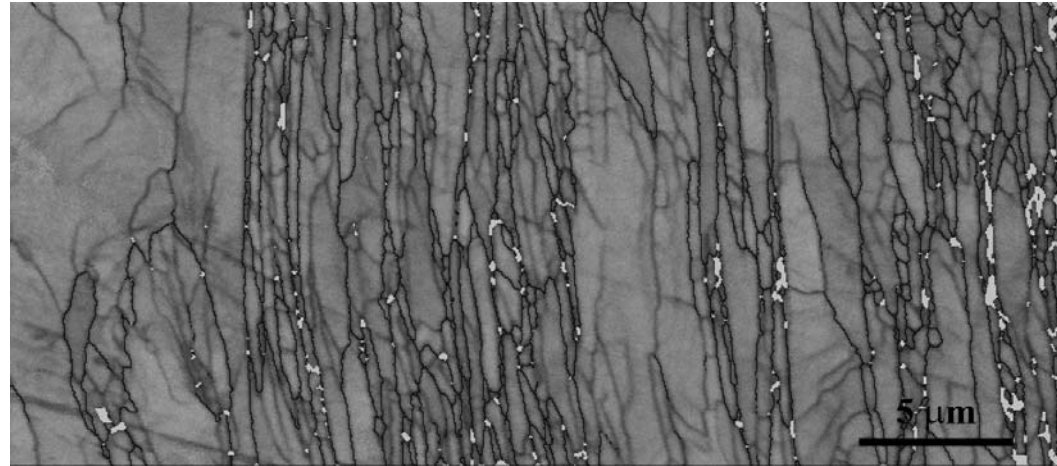
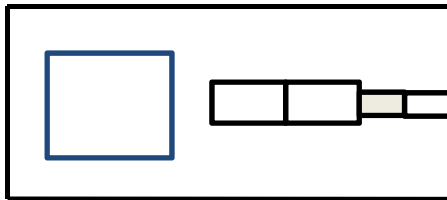
Inner

surface

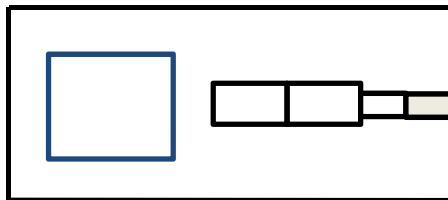
Black line: high angle boundary (Misorientation angle $> 15^\circ$)

Shot-peening (4)

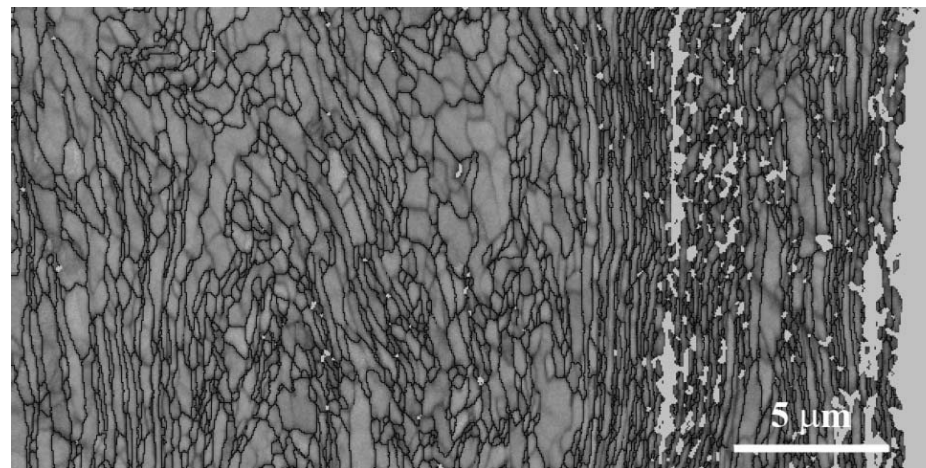
e: 60 - 30 μm from surface



f: 30 - 0 μm from surface



Inner



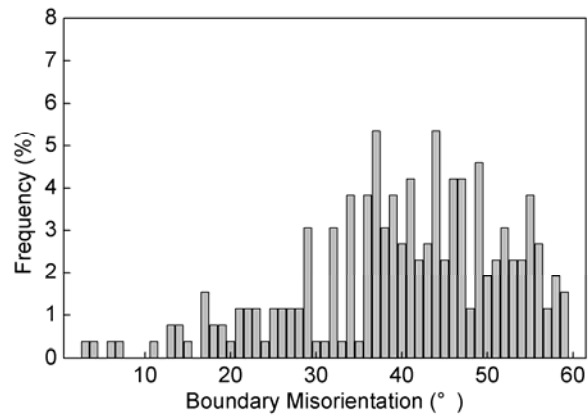
surface

Black line: high angle boundary (Misorientation angle > 15°)

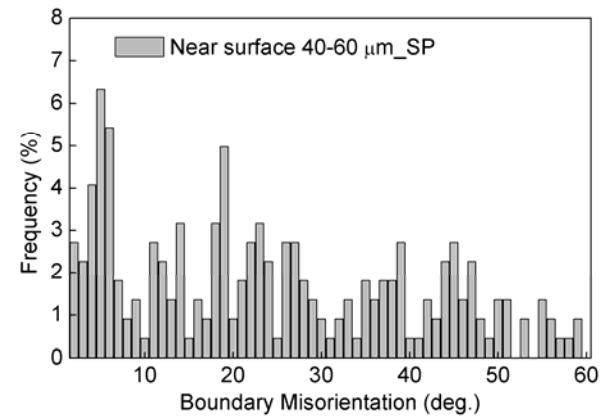
Shot-peening (5) Typical deformation structure LAB/HAB

Lamellar boundary misorientation angle (EBSD)

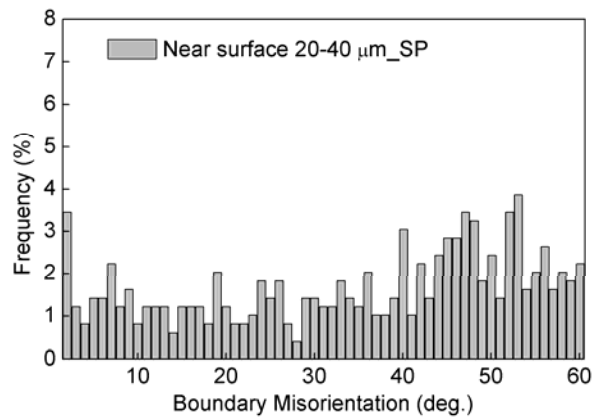
1200 - 600 μm from surface



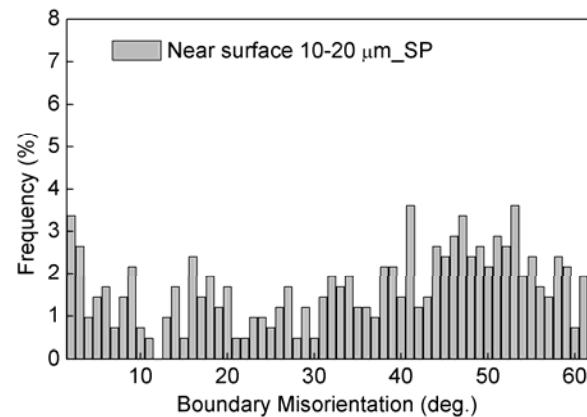
60 - 40 μm from surface



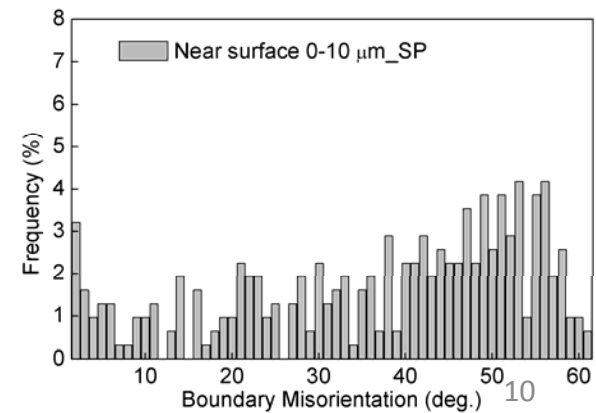
40 - 20 μm from surface



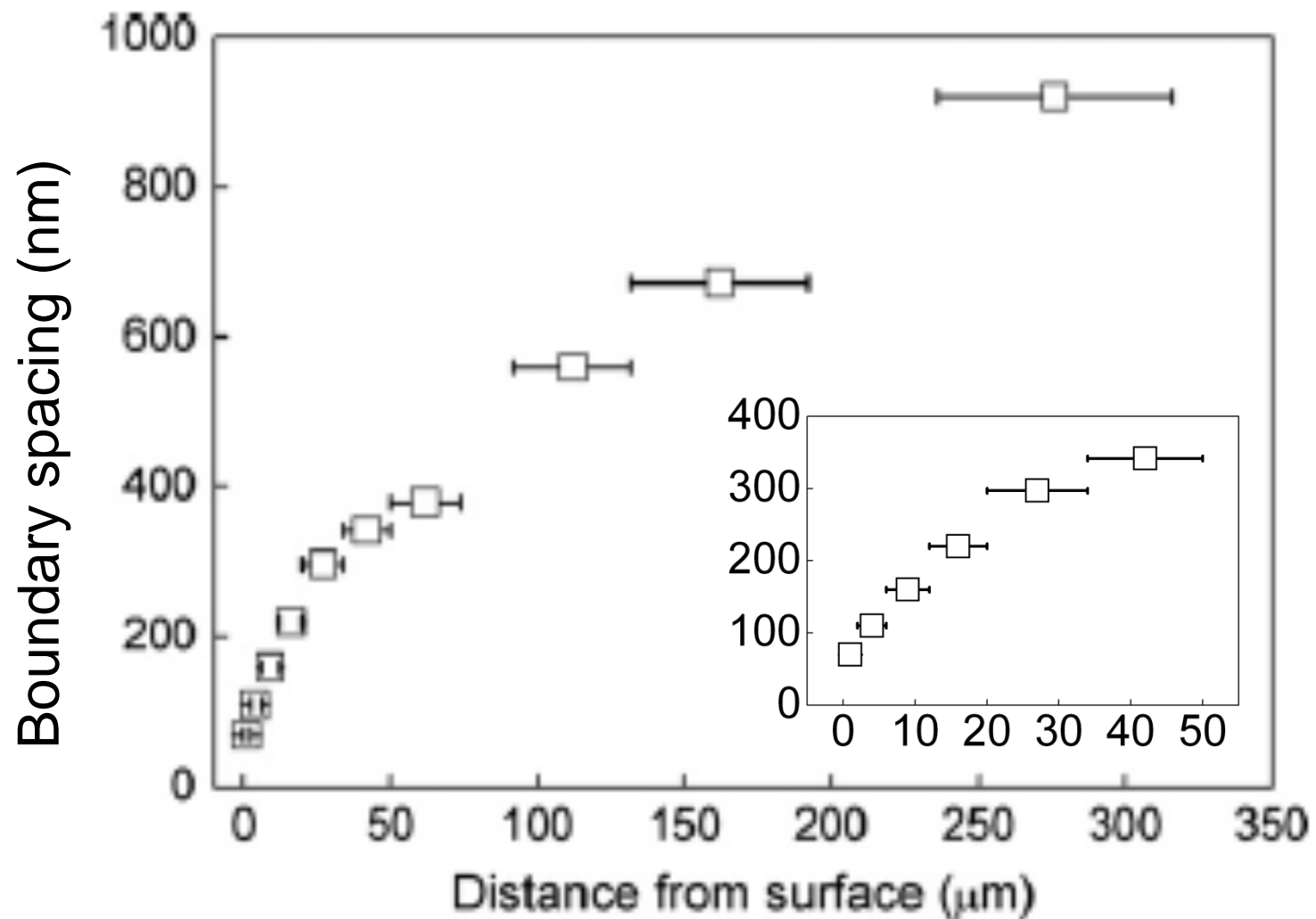
20 - 10 μm from surface



10 - 0 μm from surface

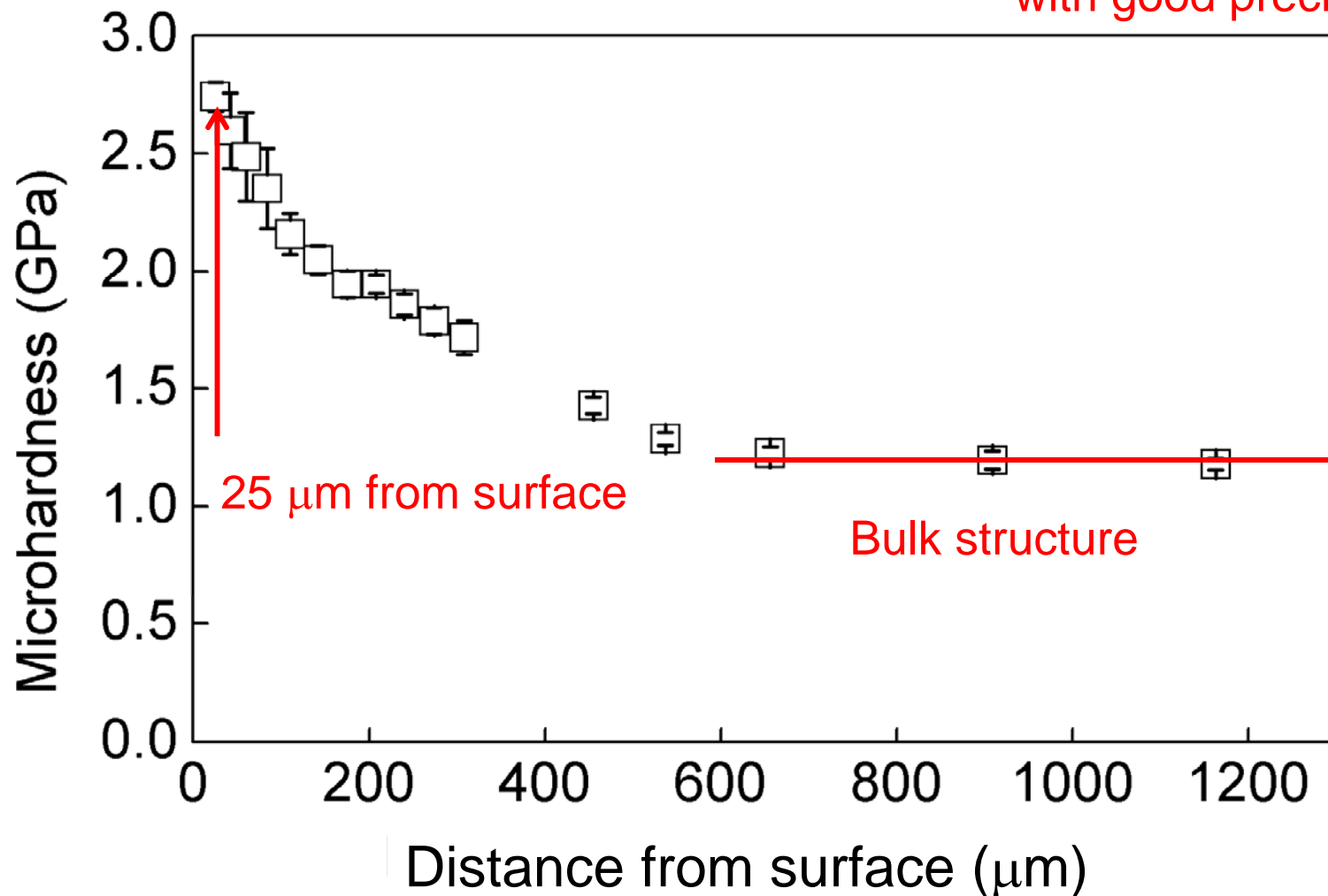


Shot-peening (6)



Shot-peening (7)

Vickers Hardness up to 25 μm from surface.
The top layer with the finest structure cannot be analyzed
with good precision.



Relationships between microstructural parameters and the stress and strain state in a gradient structure

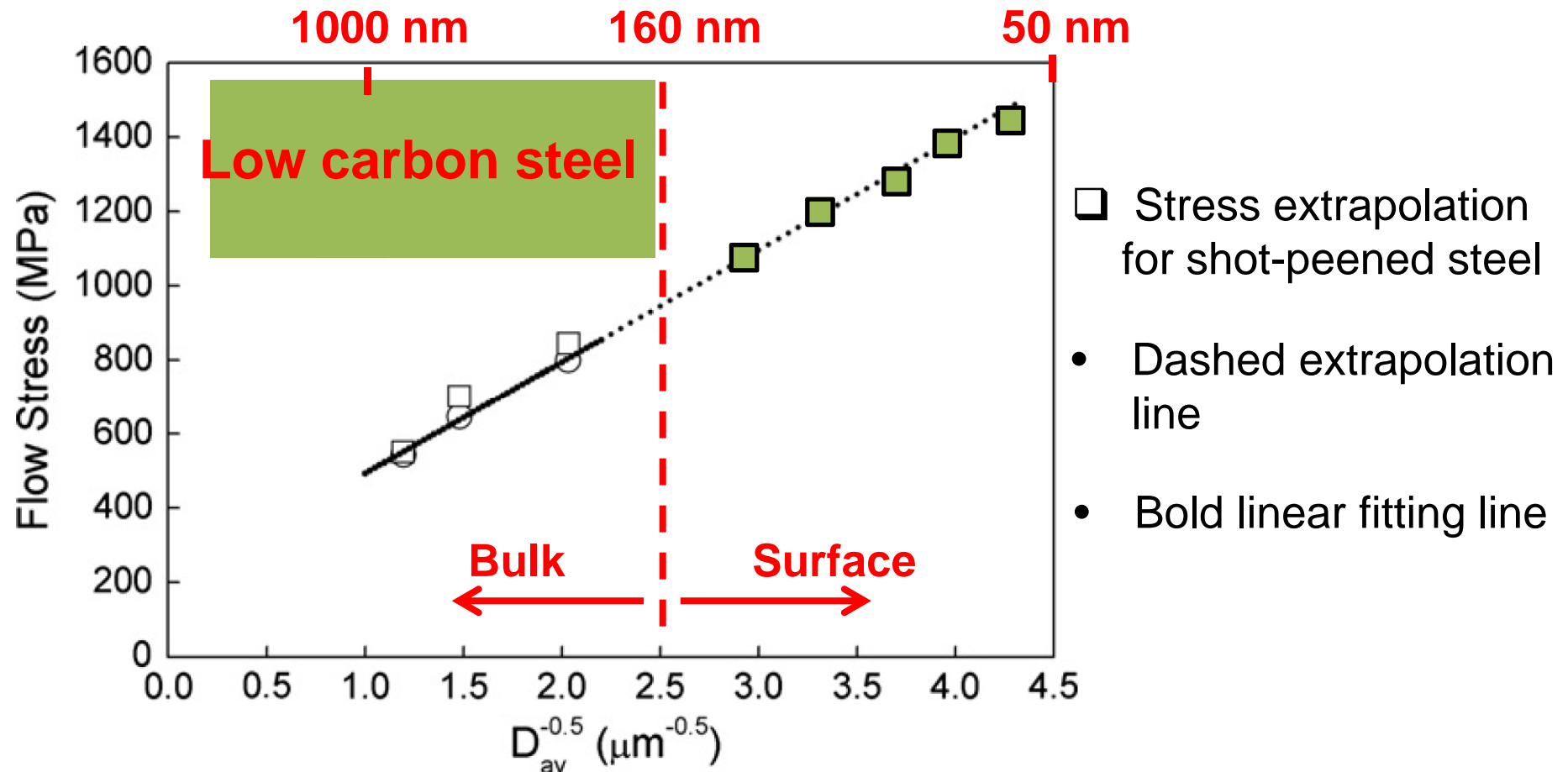
Direct estimate of stress and strain distributions in a gradient structure

- **Stress estimate: microhardness, nanoindentation, miniature test samples.**
- **Strain estimate: displacement of structural markers as grain boundaries, twin boundaries and embedded pins, neutron diffraction and high energy synchrotron X-rays.**

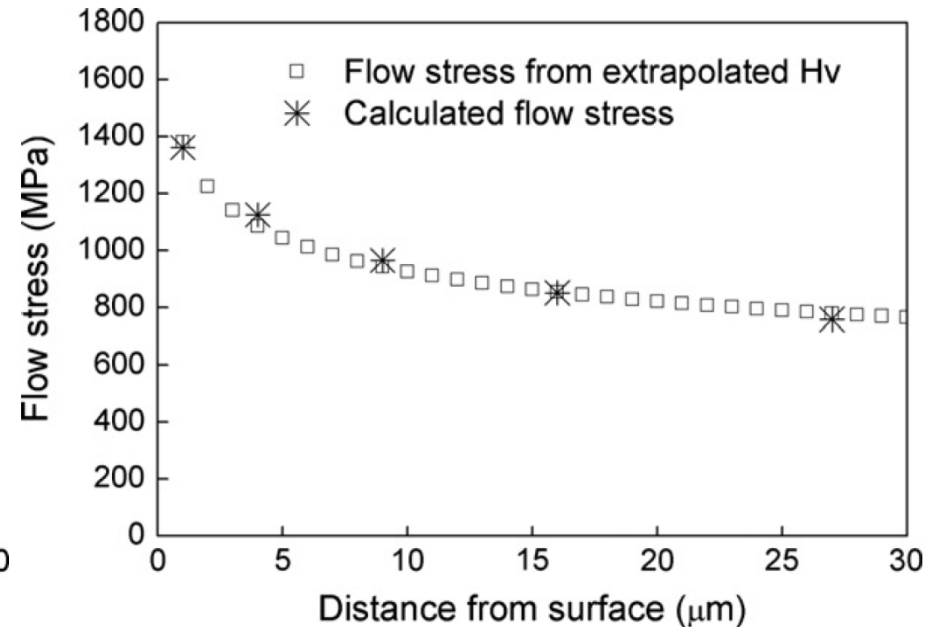
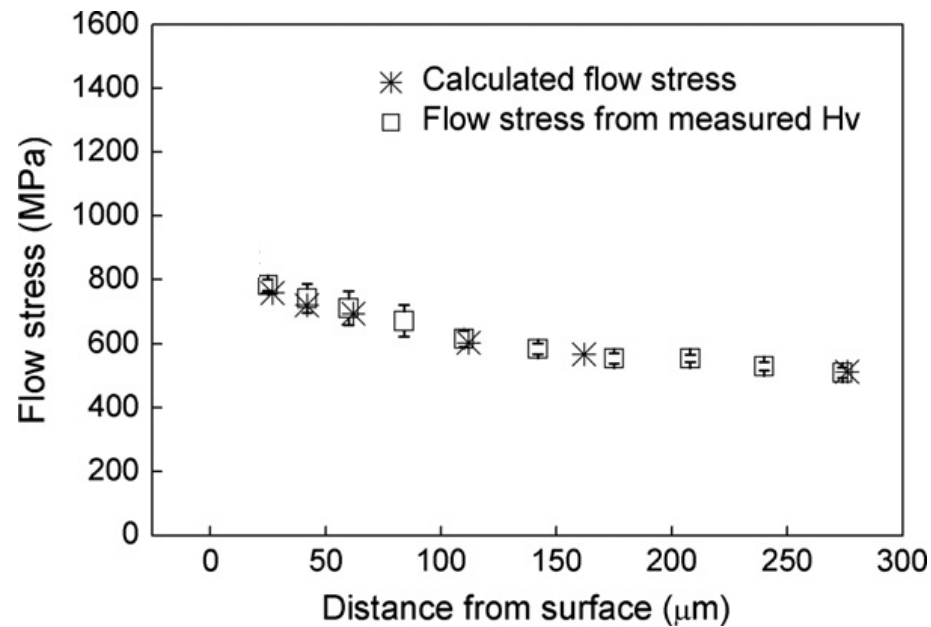
Indirect estimate of stress and strain distribution in a gradient structure

The layered structures in shot-peened, and cold-rolled samples have similar characteristics and it is suggested to use the structure-property relationships for rolled (bulk) samples as a baseline for the analysis of shot-peened samples.

Flow stress (σ) as a function of boundary spacing ($D_{av}^{-0.5}$)



Stress distribution in the gradient surface structure of a shot peened sample



Conclusions

- In medium to high stacking fault energy fcc and bcc metals, the analysis of deformed layered microstructures reveals that dislocation processes dominate from the macroscale to a limit of 5 nm, which may be reduced further.
- A gradient layered structure can be produced by surface plastic deformation reducing the structural scale to the nanometer dimension and increasing the strength to extreme values by dislocation and boundary strengthening. Structural evolution and strengthening mechanisms are promising research areas.
- Computational and materials modelling must be advanced from bulk to gradient structures. Goals are by model integration and validation to optimize processing conditions and properties (e.g. wear and fatigue) of industrial component (e.g. gears and bearings in wind generators).
- Gradient nanostructures are an important addition to the global field of nanoscience and technology.

Applications



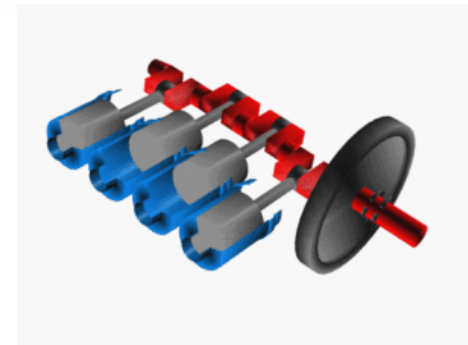
Wind energy



Gears



Bearings



Crankshafts

Applications



Wind energy



Rails



Implants

References

X Zhang, N Hansen, Y Gao, X Huang. [Hall–Petch and dislocation strengthening in graded nanostructured steel](#). Acta Materialia 2012;60: 5933-5943.